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Over the course of this project, our efforts have been focused on four distinct activities: (i) the design of locally intelligent actuators (control valve), (ii) the development of a neuromodulatory control model of the heart, (iii) development of a decentralized state estimation scheme for large scale problems, and (iv) formulation of large scale fault estimation problems using mixed integer programming. These items are highlighted in the body of this document.

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FINAL REPORT

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PUBLICATIONS RESULTING FROM THIS WORK

1. E.P. Gatzke, and F.J. Doyle III "Moving Horizon Parameter Estimation Using Qualitative Knowledge and Multiple Linear Models", *AIChE Annual Meeting*, Miami, November 1998.
2. R. Vadigepalli, F.J. Doyle III, W.C. Rose, and J.S. Schwaber, "A Second Messenger Model for Local Cardiac Control", *AIChE Annual Meeting*, Miami, November 1998.
3. R. Vadigepalli, F.J. Doyle III, "A simulation study of the nonlinear dynamic characteristics of a local reflex in the rat", *Proc. American Control Conference*, June, 1248-1252, 1999.
4. E. Gatzke and F.J. Doyle III, "Multiple Model Approach for CSTR Control", *Proc. IFAC World Congress*, July, 343-348, 1999.
5. A. Kayihan and F.J. Doyle III. "Local Nonlinear Control of a Process Actuator", *Proc. IFAC World Congress*, July, 109-114, 1999.
6. R. Vadigepalli and F.J. Doyle III, "Distributed and Decentralized State Estimation for Large Scale Process Systems", *AIChE Annual Meeting*, Dallas, November 1999.
7. E.P. Gatzke and F.J. Doyle III, "Moving Horizon Estimation and Control of an Experimental Process", *AIChE Annual Meeting*, Dallas, November 1999.
8. A. Kayihan and F.J. Doyle III, "Local Nonlinear Control of a Process Control Valve", *J. Process Control*, submitted, 1999.
9. E. Gatzke and F.J. Doyle III, "Use of Multiple Models and Qualitative Constraints for on-line Moving-horizon Disturbance Estimation and Fault Diagnosis", *J. Process Control*, submitted, 1999.
10. R. Vadigepalli, F.J. Doyle III, and J.S. Schwaber, "A Simulation Study of the Nonlinear Dynamic Characteristics of a Local Cardiac Reflex in the Rat", *Neural Computation*, submitted. 1999.

RESEARCH PROGRAM HIGHLIGHTS - LOCALLY INTELLIGENT ACTUATOR CONTROL

In hierarchical control strategies, aggressive tuning of the final control element is paramount. For low-order nonlinear systems, where the dynamics are well understood, local nonlinear control is a viable strategy to meet these aggressive demands. An internal model control strategy allows for the controller to be integrated into circuitry which may be placed on the local actuator. If preventative measures are necessary, fault detection may be implemented by on-line estimation of system critical parameters. Interpretation of these parameters allow for adaptive measures to be taken to maintain high levels of controller performance.

A state-space model of a pneumatic process valve is developed using force balances on valve components and friction effects which provides for exact representation of valve parameters without loss of manageability. From this, a model-based, nonlinear local control strategy is developed for a process valve, NLIMC. As measured by integral absolute tracking error, this local strategy have been proven to perform more proficiently than traditional linear control in the presence of parametric disturbances while providing smooth control action. On-line self-diagnostic measures are provided using residual evaluation, fault-trees and nonlinear least squares parameter fitting which are all facilitated by a nonlinear Luenberger parameter observer. A local nonlinear control strategy is thereby presented for a pneumatic *push-down-to-close* valve. Although there have been many efforts made in friction and actuation modeling, no continuous state-space models of a sliding-stem process valve have been published to date. The application of discontinuity smoothing for use in differential methods to compensate for the inherent friction nonlinearities in process valves and to provide smooth control action have not been published to date.

NLIMC makes an ideal algorithm for a digital controller which can be placed on a circuit board locally on the actuator. Model Predictive Control (MPC) is computationally cumbersome and is not viable, using current hardware, for implementation on a micro-chip. Rather than solving an optimization problem in the future, IMC computes control action for the next time period. Linear IMC is the simplest model-based controller, and under ideal conditions, it can be reduced to a PID algorithm. The transition from linear to NLIMC is not difficult due to the fact that the input-output linearization map is an algebraic function and the systems of differential equations, which make up the Luenberger observer, may easily be solved for one time step. This makes NLIMC a viable control algorithm for local control of an actuator.

RESEARCH PROGRAM HIGHLIGHTS - SECOND MESSENGER MODELING OF LOCAL LOCAL INTELLIGENT CONTROL IN BARORECEPTOR VAGAL REFLEX

The Nervous System in living organisms exhibits high performance robust control of complex underlying systems. It has been demonstrated that this natural "control system" achieves tight regulation of biological systems under a variety of physiological operating conditions and stringent performance requirements. Hence, there is a clear incentive for a systems engineer to study the control structures in living systems and reverse engineer the principles for applications in control systems engineering. The neuronal control principles obtained through this *neuromimetic* approach could be applied in process controller scheduling, nonsquare controller design, and dynamic process modeling. The novel control algorithms thus designed could be utilized in automated industrial processes to enable tightly regulated operations with respect to environmental emissions, while at the same time satisfying the performance and quality requirements demanded by the global competitive market.

The system under study in this project is the baroreceptor vagal reflex (responsible for short term blood pressure control). The main objective of this work was to quantitatively study the local control aspects of the baroreceptor reflex and understand the interactions between higher levels of central nervous system and local control structures. The anatomical experimental studies in our laboratory have shown the existence of a local reflex in the rat. SIF neurons receive cardiac sensory inputs from the atrial receptors and then project to the Principal Neurons (PNs). Specific PNs also receive extremely dense input from the dorsal motor nucleus of the vagus (DMV). The firing activity of the PNs regulates the heart beat cycle via modulation of the Sino-Atrial node, thus completing the local reflex loop. In the guinea-pig and mudpuppy, similar local reflexes are proposed in the literature. This study involved the development of a mathematical model for the local cardiac reflex, and through simulations analyze the role of local reflex in cardiac regulation and then verify the model predictions through experimental studies.

The representative mathematical model constructed is *neuromorphic* in that it is based on the anatomical and physiological data available from other laboratories and literature. This model incorporates second messenger reaction kinetics and calcium dynamics to represent the nonlinear dynamics and the crucial role of neuromodulation in local control. This *neuromorphic* approach is inspired by studies in vision and motor control that have begun to yield results in object recognition and robotic control, respectively.

The following key assumptions have been employed in the derivation of the model: *(i): The SIF cells in the cardiac ganglia innervate the principal ganglion neurons in their vicinity.* This assumption is supported by the early work that the SIF cells in the rat sympathetic ganglion synapse on the PNs and the more recent work that SIF cells in the mudpuppy cardiac ganglion make close contacts with the PNs. *(ii): SIF cells are interneurons in rat cardiac ganglia and contain neural modulator 5HT, just as those in the sympathetic ganglia. (iii): Stimulation of atrial receptors causes a non-pulsatile release of 5HT from the SIF cells, which in turn increases the conductance of a potassium channel of the principal ganglion cells through a similar second messenger pathway as the one in the R15 neurons in Aplysia* and hence inhibits PNs. This assumption is based on the similarity of the second messenger pathways between the sympathetic ganglion and the ganglion in the Aplysia. *(iv): The baroreceptor reflex loop is dormant and the principal neurons receive a periodic vagal drive.*

Simulations indicate that the functional role of the local reflex is nonlinear compensation between the vagal input from DMV and the mean arterial blood pressure. This hierarchical input-output linearizing structure is well known and studied in systems engineering. "Linearizing" reflexes are demonstrated and well studied in the visual system (Vestibular-Ocular reflex). The dynamic neuromodulation as a mechanism for the nonlinear attenuation is the novel result of this study. Earlier simulations have shown that this local cardiac reflex structure could be a putative mechanism for the Bainbridge reflex.

These simulation studies support the general intuition that the local cardiac reflex is indeed playing an "integrative" role in overall cardiac regulation. The experimental verification of the model predictions needs to be performed. Cardiovascular regulation is distributed and hierarchical in nature without an apparent control objective (*setpoint* in control paradigm). We have explored the information fusion aspects of overall cardiovascular control to better understand the mechanisms that contribute to the robust performance. Those ideas have lead to the state estimation results described in the next section

Research Program Highlights - Large Scale Distributed and Decentralized State Estimation for Large Scale Process Systems

Chemical plants employ a variety of heterogeneous and redundant multisensor systems to obtain dynamic information. As the sensor and data acquisition technology improves, an overwhelming amount of information is available in chemical process plants. For effective plant-wide operation, this information needs to be "combined" and "interpreted" in such a way that a reliable. complete and coherent description of the system is obtained. This study deals with a quantitative approach to solve this "data fusion" problem. While detailed and improved mathematical models of various components of plant-wide systems are being developed, state-space based methods for monitoring and controlling these systems are attracting research attention. All of these methods invariably involve potentially nonlinear state estimators in the final design. The centralized structure that is traditionally used with the existing estimation algorithms is not scalable to large-scale plant-wide systems. Although the computational capability of the central processor is an issue, the algorithmic scalability is critical. Recent results in multisensor data fusion show that the fully distributed and decentralized estimation structure provides the required scalability and at the same time retains the global optimal performance that is equivalent to that of a centralized fusion system.

A fully decentralized system is a data processing system in which all the information is processed locally and where there is no central processing site. Each sensor (fusion) node contains its own processing facility and obtains local observations; relevant information is then shared with the other nodes to compute a global optimal estimate. Each node "knows" only a part of the global state space of the plant-wide system. The computation and communication is distributed over the network such that global optimal state estimates are produced. This network-based computation is the key property that makes it scalable to large-scale plant-wide applications. It is also robust to the loss of measurements as the estimation network naturally "tunes" the algorithm to obtain the global optimal estimate.

Distributed and Decentralized Fusion (DDF) has been successfully applied to several low-order mechanical and aeronautical systems. This study examines the issues of using scalable DDF for complex large-scale plant-wide chemical systems. The system considered is an industrial benchmark problem published in the literature. This complex process involves three distillation columns, two reaction steps and two recycle streams. A state space mathematical description of this plant consists of 660 states, 12 inputs (manipulated variables and disturbances), and 90 outputs (measured variables and control variables). This process, like any other plant-wide system, is hierarchical and distributed, *i.e.*, it can be visualized as a network of "processing nodes" that are interconnected to each other. In this case, the "processing nodes" are the distillation columns, reactors, reboilers and condensers that are part of the plant. The DDF structure takes advantage of this distributed nature, and it can be thought of as a "replicated image" of the interconnected physical components of the plant. An open-loop distributed and decentralized Kalman filter is designed for this benchmark plant. The estimation network designed provides adequate performance in simulation studies.

The issues involved in employing the nonlinear form of the distributed estimation algorithm, specifically in balancing the computational load vs. communication overhead, continue to be studied in our group. The scalable approach could be extended to advanced control algorithms. so that an integrated framework for combined estimation and control for large-scale process systems could be developed.

Research Program Highlights - Large Multiple Model and Mixed Integer Approaches to Estimation

Real process systems can experience significant disturbances that adversely affect the process. To quickly correct the situation, the source of a fault must quickly be identified. In some cases, it is also useful to develop an estimate of the extent of the disturbance on the system so that corrective actions can be taken. There are many labels for this type of problem, including: disturbance estimation, on-line parameter estimation, state estimation, and fault diagnosis.

Traditional estimation methods include the Kalman Filter for linear systems and the Extended Kalman Filter for nonlinear systems. Moving horizon estimation methods have recently been used for estimation applications. Moving horizon estimation methods create a constrained optimization problem to be solved at each sampling time using a process model and a finite set of process measurements across a receding horizon. Recently, researchers have proposed the use of integer variables and propositional logic constraints for estimation and control. The presence or absence of a process fault can be represented using binary variables. The resulting mixed integer problem must be solved online.

The current work has focused on extensions of moving horizon estimation methods which include logic constraints. Propositional logic constraints have been developed implement the assumption that only a limited number of faults may occur in a horizon window, allowing diagnosis and estimation of systems that fail traditional observabilty criteria. Multiple model representations can be used, allowing for estimation of nonlinear dynamic systems that exhibit variable process gains and dynamics. Model weights are not explicitly calculated for the system; instead, the optimization problem picks the best combination of set of models available for a disturbance. Online solution strategies have been explored to minimize the solution time for the mixed integer optimization problem. This method has been examined for systems with up to twenty faults.

There are many potential interesting applications of mixed integer formulations to process systems problems. Integer variables can be used in constrained optimization problems to represent general logical statements. These logic statements can be used to express knowledge about a system. In the current work, logic constraints express assumptions about the limited number of occurring faults. In other applications, controllers can be developed for hybrid systems (systems involving discrete states, such as an on-off actuator). Controllers can also be developed based on a prioritized objectives quickly and intuitively. Mixed integer applications to process systems engineering problems bridge the gap between continuous applications (traditional control and estimation methods) and discrete applications (rule-based expert systems and discrete event systems). Developments in computational power, parallel processing, and algorithm engineering will allow for on-line solution of mixed integer optimization control and estimation problems that accurately describe the true process relationships and objectives.